Materials Science & Engineering A 607 (2014) 460–475

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Microstructure evolution and mechanical properties of a hot-rolled directly quenched and partitioned steel containing proeutectoid ferrite

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ARTICLE INFO

Article history:
Received 14 January 2014
Received in revised form
2 April 2014
Accepted 4 April 2014
Available online 13 April 2014

Keywords:
HDQ&P steel
Proeutectoid ferrite
Microstructure
Mechanical properties

ABSTRACT

A low carbon V microalloyed steel was treated by hot-rolling direct quenching and partitioning (HDQ&P) processes. The microstructures were characterized by polygonal proeutectoid ferrite and lath martensite accompanying with both blocky and film-like retained austenite. This kind of HDQ&P steel possesses a lower yield ratio and similar tensile strength and elongation when compared with the existing HDQ&P steel without ferrite. Partitioning processes with different time were designed to optimize the characteristics of the retained austenite and to control its stability. The microstructure–properties relationship, the stability of the retained austenite, and the transformation-induced plasticity (TRIP) behavior were investigated by comparing the microstructures and mechanical properties of the HDQ&P sheets with those of the TRIP sheets. The results show that the introduction of proeutectoid ferrite can ensure the low yield strengths of the materials and simultaneously intensify the inhomogeneous distributions of carbon and silicon in the untransformed austenite. The particular element distributions result in a considerable amount of large blocky retained austenite locating on the ferrite/martensite boundaries or in some regions surrounded by ferrite. The high tensile strength of the HDQ&P steel can be attributed to the major martensitic structure, the V-bearing precipitates in ferrite and the TRIP effect of the retained austenite. The outstanding combination of strength, yield ratio and ductility, which synthesizes the advantages of dual-phase (DP) steel, TRIP steel and Q&P steel, indicates that the HDQ&P steel has a great potential for practical application.

1. Introduction

In order to resolve the contradiction between fuel consumption and safety in the automobile industry, the development of new advanced high strength steels (AHSS) with adequate properties of strength and ductility has attracted much attention in the past few decades [1,2]. The currently studied steel so called quenched and partitioned (Q&P) steel is one of the most attractive AHSS for its excellent combination of mechanical properties which has been recently developed based on the 1st generation AHSS (such as dual-phase (DP) steel, transformation-induced plasticity (TRIP) steel and martensitic steel) and the 2nd generation AHSS (twinning-induced plasticity (TWIP) steels) [3–5]. The Q&P heat treatment proposed by Speer et al. mainly includes three steps as follows [6]. Firstly, a fully or partially austenitised steel is quenched to a desired temperature between the martensite start (M_s) and finish (M_f) temperatures to form a mixture of martensite and untransformed austenite. Secondly, an isothermal partitioning treatment is carried out at a temperature no less than the quenching temperature to accomplish carbon partitioning from the supersaturated martensite to the untransformed austenite. Finally, the steel is cooled to room temperature and the microstructure consisting of martensite and the retained austenite is obtained [7–9].

Up to now, a substantial amount of the Q&P research has focused on the Q&P treatments containing reheating processes, i.e., the hot-rolling off-line Q&P treatment and the Q&P treatment of cold-rolled sheet [10–13]. In the past two years, a novel energy-efficient concept of hot-rolling direct quenching and partitioning (HDQ&P) process has been proposed with the aim of making use of the residual heat of hot-rolling effectively in the partitioning step and producing ultrahigh-strength steel with excellent ductility [14]. Although the feasibility of the HDQ&P process and its potential to improve the mechanical properties have been proved by some researchers [14,15], the microstructure–properties relationship and the effective control of the amount and stability of the retained austenite in HDQ&P steels have not yet been investigated in detail. Simultaneously, more attention in Q&P steels has been focused on a dual-phase microstructure mixed with martensite and retained austenite for the purpose of obtaining the ultra-high strength. The traditional Q&P steels consisting of dominating martensite and a small amount of

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http://dx.doi.org/10.1016/j.msea.2014.04.030
0921-5093/

retained austenite usually have high yield strengths coupled with high yield ratios, which can result in a loss in formability. In fact, some researchers have proved that the introduction of ferrite, as a soft phase, into Q&P steels can further improve the properties [1]. However, the specific effects of the ferrite on the solute atom distribution in matrix and the amount, morphology and stability of the retained austenite are still unclear.

In this work, HDQ&P processes with different partitioning time have been carried out based on the thermo-mechanical control process (TMCP) and the ultra-fast cooling (UFC) technology. Proeutectoid ferrite was introduced into the present steel. The microstructure–properties relationship and the effects of the ferrite on the evolution of the retained austenite in the Q&P sheets have been investigated and compared with those of the hot-rolled TRIP sheets with the same composition.

2. Experimental material and procedure

An ingot of the vacuum-melted low carbon V microalloyed steel (Fe–0.21C–1.67Si–1.65Mn–0.2V wt%) was forged into a billet with a section dimension of 60 mm × 60 mm. The critical temperatures were measured by dilatometer analyses, leading to A_{C1}=707 °C, A_{C3}=905 °C, A_{r1}=580 °C, A_{r3}=760 °C, M_s=388 °C and M_f=150 °C.

Both hot-rolling directly isothermal bainite treatments (i.e., hot-rolled TRIP treatment, hereafter referred to as TRIP) and HDQ&P treatments (hereafter referred to as Q&P) were respectively carried out in this work, and the schematic thermal profiles of the processes are illustrated in Fig. 1. The slabs with the same thickness of 60 mm were austenized at 1200 °C for 2 h and then hot-rolled to 15 mm through 3 passes at temperatures above 1000 °C. After being air-cooled to 950 °C, the plates were again hot-rolled to 4 mm through 4 passes with a finish rolling temperature of about 820 °C and then air-cooled to about 785 °C. Next, two sheets (Nos. 1 and 2) were directly quenched to about 550 °C (540 °C for No. 1 and 550 °C for No. 2) and then isothermally treated at 390 °C for 1 min (No. 1) and 2 min (No. 2) in a resistance heating furnace respectively, and finally air-cooled to room temperature. Another four sheets (Nos. 3, 4, 5 and 6) were directly quenched to the range of 245–290 °C (the actual temperatures for No. 3, No. 4, No. 5 and No. 6 sheets are 245 °C, 290 °C, 286 °C and 275 °C, respectively), followed by partitioning in a resistance heating furnace at 390 °C for 1 min (No. 3), 2 min (No. 4), 5 min (No. 5) and 15 min (No. 6), respectively, and finally air-cooled to room temperature.

Tensile specimens with a gauge portion of 5 mm in width, 4 mm in thickness and 25 mm in length were cut with their longitudinal axes parallel to the rolling direction. The geometry of the tensile test specimen is schematically shown in Fig. 2. The tensile test was performed on a CMT5105-SANS machine at room temperature with an extension speed of 1 mm/min. Three specimens for each process were used and the average values were calculated.

The volume fraction and average carbon concentration of the retained austenite were measured at room temperature using a D/max 2400 X-ray diffractometer (operated at 56 kV, 182 mA). Three specimens for each process were used and the as-rolled surface of each specimen was detected and then the average values were calculated. During the experiment a 2θ range from 40° to 120°, containing the (200), (220), (311) and (222) austenite peaks and the (110), (200), (211) and (220) ferrite peaks, was step-scanned with a scanning speed of 2°/min. The specimens for X-ray diffraction (XRD) measurements were mechanically ground and finally electro-polished to minimize the possible error resulting from the mechanically induced transformation of retained austenite during the preparation of the specimens. The details of the method to determine the exact values of the volume fraction and average carbon concentration can be found in the published articles [16–19].

Microstructure observation was carried out using a Leica DMIRM optical microscope (OM) and a JXA-8530F electron probe microanalyzer (EPMA). Selected specimens were evaluated by a Zeiss Ultra-55 field emission scanning electron microscope (SEM) equipped with an electron backscattered diffraction (EBSD) system and a transmission electron microscope (TEM-TECNAI G220) at an accelerating voltage of 200 kV. The specimens for the OM observation and EPMA observation were ground and polished mechanically then etched by 4% nital for about 15 s. For the EBSD measurement, the specimens were first ground then electro-polished with an electrolyte consisting of 650 ml alcohol, 100 ml perchloric acid and 50 ml distilled water at room temperature

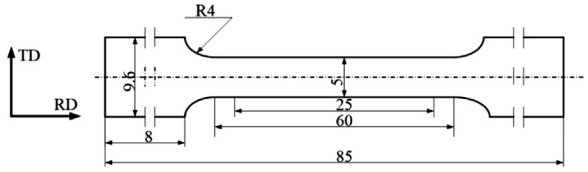

Fig. 2. Geometry of the tensile test specimen. All the dimensions provided are in millimeters. "TD" is transverse direction; "RD" is rolling direction.

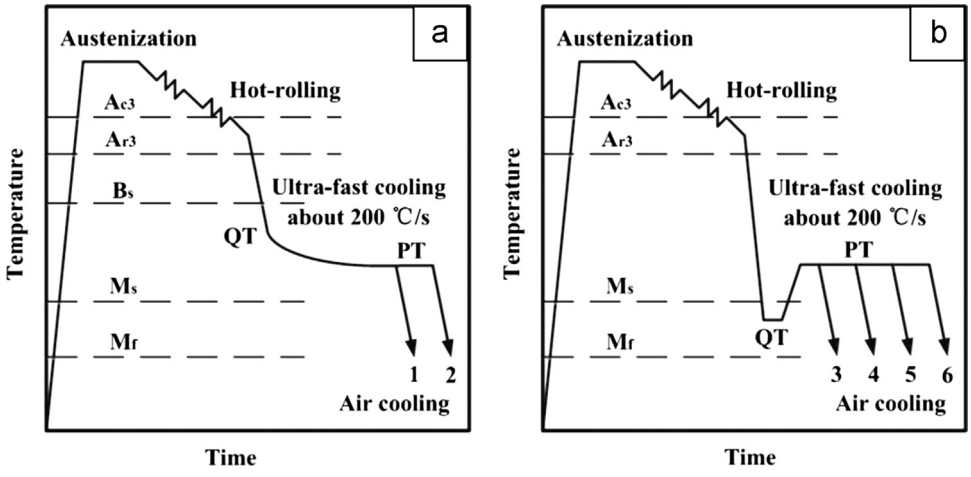

Fig. 1. Schematic thermal profiles of the processes: (a) TRIP and (b) Q&P.